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CUMULATIVE BEAM BREAKUP OF THE GROUND-BASED FREE-ELECTRON LASER*

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Abstract

Strategies employed by the Ground-Based Free Electron Laser system to maintain beam stability in its rf linac against cumulative beam breakup will be described. These strategies include a proper choice of cavity shape and the use of staggered tuning. Simulations show that the growths of effective transverse emittance due to cumulative beam breakup can be limited to 10%.

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Introduction

The Ground-Based Free Electron Laser (GBFEL) is a high-power free electron laser (FEL) system being built at the White Sands Missile Range. Because of the high average current and large number of cavities, the rf linac which provides the electron beam is susceptible to cumulative beam breakup.

The physics of cumulative beam breakup (CBB) has been well described in the literature [1,2]. Like most other beam breakup phenomena in linacs, CBB is caused by excitations of dipole modes in accelerating cavities by transversely displaced beam. The excitation of a dipole mode in a cavity can in turn cause later beam bunches to develop transverse displacements. These displacements, being induced by a dipole mode, have the frequency of the dipole mode. When the beam bunches arrive at the following cavities, they will resonantly excite the same dipole mode in these cavities. For an rf linac with many cavities and high average current, large oscillations of the transverse displacements of beam bunches will develop, causing beam loss and effective transverse emittance growth.

The growth of CBB can be reduced by choosing a cavity shape with small coupling between a beam and the dipole modes. It can also be reduced by employing staggered tuning. Staggered tuning means having slightly different dipole-mode frequencies among cavities so that the condition for resonantly exciting the same dipole mode in all the cavities does not exist. In this paper, we will describe how the selection of a cavity shape was made for GBFEL. We will also describe the staggered-tuning strategies that we plan to employ and how they have been tested using computer simulations.

Cavity shape

For many years, accelerator cavities in rf electron linacs have been designed solely toward achieving high power efficiency. Cavities so designed usually have relatively small beam apertures and short accelerating gaps with nose cones. A typical high-efficiency cavity is shown in Figure 1. These cavities, though highly efficient in accelerating electrons, are very disruptive to the accelerated beam because they are equally efficient in exciting higher-order modes, including the dipole modes. The excitations of higher-order modes can cause deterioration of beam quality through CBB and single-bunch beam loading. Since good beam quality is extremely important for a FEL system to achieve high gain, a cavity shape used in a FEL system should be designed in terms of beam quality as well as power efficiency. The shape chosen should be a compromise between beam quality and power efficiency.

The cavity shape chosen for the GBFEL cavity is shown in Fig. 1. The cavity parameters are compared to those of a high efficiency cavity in Table 1. This shape was designed to reduce the transverse coupling impedances to dipole modes. Transverse coupling impedance R is a measure of the efficiency of a beam exciting a dipole mode and is defined, following Ref. 2, as

$$\frac{R}{Q} = \frac{2}{\omega\varepsilon_0} \frac{\left| \int_0^L dz \exp(-i\frac{\omega z}{c}) \frac{\partial E_z}{\partial x} \right|^2}{\int_V E^2 \, dv} .$$

where $\partial E_z/\partial x$ is the gradient of the longitudinal field in the transverse direction x, L is the length of the cavity, and $(\varepsilon_0/2)\int_V E^2 dv$ is the total energy of the deflecting mode in the cavity.

The GBFEL cavity has a relatively large beam-aperture radius of 5 cm compared to a high-efficiency cavity, because R decreases roughly as the second power of the aperture radius and the use of larger beam apertures is encouraged. The beam aperture is limited to 5 cm because it will be impractical to build a beam-transport system with a beam aperture larger than 5 cm.

The GBFEL-cavity shape, similar to those found in superconducting linac, has a long accelerating gap without nose cones, because transit-time effects have been used to reduce the coupling impedance for the dipole modes. In principle, the excitation of a dipole mode can be reduced to zero if the accelerating gap has a length corresponding to one wavelength of the dipole-mode frequency; a beam bunch traversing the gap will spend half a cycle exciting the dipole mode and half a cycle deexciting the dipole mode. The accelerating-gap length of the GBFEL cavity is chosen as 34 cm, which is relatively long compared to the high-efficiency cavity and is roughly equal to the average wavelength of the three most important dipole modes in the cavity.

The GBFEL cavity has been designed to achieve better beam quality by sacrificing power efficiency. The shunt impedance of the accelerating mode of the GBFEL cavity is only 66% of the shunt impedance of a high-efficiency cavity.

Simulations

Although the expected growth of CBB has been reduced by a choice of cavity shape, the amount of growth expected has to be computed using computer simulation. Results of these simulations are summarized in this section.

The section of the GBFEL linac simulated was that between 14.4 and 100.0 MeV. It is made up of twenty modules shown schematically in Fig. 2. A module consists of two pairs of accelerating cavities, a focusing quadrupole, and a defocusing quadrupole. The quadrupoles have field strengths of 40 G/cm at a beam energy of 20 MeV. Their strengths increase linearly with the beam energy to form a lattice with constant-focusing strength.

The beam parameters used were: normalized 90% transverse emittance of 25 π mm mrad, bunch charge of 8 nC, and bunch frequencies of 27 and 75 MHz for average currents of 0.22 and 0.6 A respectively.

The nominal R/Q and Q values of dipole modes of a GBFEL cavity were respectively 12,000 Ω/m^2 and 52,623. They correspond to the values of a TM_{121}-like mode and is the largest R/Q among the low-lying deflecting modes The mode frequency is 896 MHz.

Simulations were performed by tracking bunches through the linac according to a prescription outlined in Ref. 2 [3] and computing the effective transverse emittance at the end of the linac. Results are summarized in figures plotting the emittance-growth factor versus tolerance. In these figures, the term "tolerance" defines the quality of a beam required entering the linac. A tolerance, for example, of 1×10^{-5}, means that the beam bunches enter the linac with random displacements in a range of $\pm1\times10^{-5}$ m (10 μm) and random divergences in a range of $\pm1\times10^{-5}$ rad (10 μrad). The distributions of the random displacements and divergences in the ranges are uniform. As a rule, a beam is considered stable if an emittance-growth factor of less than 10% can be maintained with a reasonable tolerance of 10^{-4} (0.1 mm and 0.1 mrad) or higher. The 10% emittance-growth levels are indicated in the figures as the "10% line".

The results of simulations of a beam with average current of 0.22 A going through the linac are shown in Fig. 3. These results show that, without staggered tuning, a tolerance of 4×10^{-6} is required to maintain an emittance growth of less than 10%. It also shows that the linac will be stable with a staggered tuning of 40 kHz. A staggered tuning of 40 kHz means that the dipole-mode frequencies of different cavities are different with values populating uniformly a range of ±40 kHz of the nominal dipole-mode frequency. A staggered tuning of 40 kHz has the special significance that it corresponds to the frequency variance of cavities with machining tolerance of ±0.5 thousandths of an inch. We will henceforth call this amount of staggered tuning as the "natural" staggered tuning.

Figure 4 shows simulation results for a higher average current of 0.6 A with differing amounts of staggered tuning. The figure shows that a 10^{-4} tolerance is acceptable only when more than 100 kHz of staggered tuning, in excess of natural staggered tuning, is used.

Two strategies have been tested with simulations to achieve staggered tuning with a range higher than the 40 kHz from the natural staggered tuning. First, one can actually built two sets of cavities which have different dipole-mode frequencies. The solid curve in Figure 5 shows simulation results when alternate modules have dipole-mode frequencies differing by 200 kHz. Together with a natural staggered tuning of 40 kHz, a beam of 0.6 A will be stable. Second, the rf feed will destroy the degeneracy of the two orthogonal dipole modes in an accelerator cavity. Frequencies of these modes will be different by 100 kHz or more and the Q-value of one mode will be degraded to 10 000 [4]. The different frequencies and lower Q can be used to our advantage. We can rotate the rf feed to alternate modules by 90°. By doing this, we have, in equivalent, a system with alternate modules having dipole-mode frequencies differing by 100 kHz and effective deflecting-mode suppressed in alternate modules. The dashed curve in Fig. 5 shows that, coupled with a natural staggered tuning of 40 kHz, a beam of 0.6 A can be kept below 10% if a tolerance level of 2×10^{-4} is met. In fact, the two ways described here can be combined. The simulation results are shown in Fig. 5 as the dash-dotted curve. In this case, only a tolerance of 1×10^{-3} is required.

Summary

The transverse emittance growth due to cumulative beam breakup in the rf linac of the GBFEL has been limited to 10% with a reasonable tolerance required on beam quality at the entrance of the rf linac. Such a stable beam with average current up to 0.6 A is achieved by properly choosing a cavity shape and by employing staggered tuning.

References:

1. K. C. D. Chan, "Long-Range Wakefield Effects in Rf-Based Free-Electron Laser", Proceedings of the Free-electron Laser seminar, August 11-23, 1988, Peking University, Beijing, Peoples Republic of China, Beijing Institute of Modern Physics Series, published by World Scientific, Singapore.

2. R. L. Gluckstern, R. K. Cooper and P. J. Channell, "Cumulative Beam Breakup in Rf Linac", Particle Accelerator, **16**, pp125-153, (1985).

3. Equations 16 and 17 in Ref. 2.

4. A. Vetter, Boeing Aerospace Corporation, private communication.

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Table 1

A comparison of cavity parameters for a high-efficiency (HE) cavity and a GBFEL cavity, ZT^2 =shunt impedance of accelerating mode, R=transverse coupling impedance, Q=Q-value.

	HE Cavity	GBFEL Cavity
outer radius (cm)	23.5	29.8
aperture radius (cm)	2.5	5.0
gap length (cm)	20	34
ZT^2 (MΩ)	12.83	8.50
R/Q (Ω/m²)	18021	12000
R (MΩ/m²)	1146	631

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Figure caption

Fig. 1. Cavity shapes of a typical high-efficiency (HE) cavity (dashed) and a GBFEL cavity (solid).

Fig. 2. Schematic drawing of an accelerating module of the GBFEL linac.

Fig. 3. Emittance-growth factors as a function of tolerance of beam coordinates at an average current of 0.22 A, with (dashed curve) and without (solid curve) 40kHz of staggered tuning.

Fig. 4. Effects of staggered tuning on emittance-growth factors at an average current of 0.6 A.

Fig. 5. Effects of different strategies of staggered tuning. Natural staggered tuning has been assumed in all the curves. The solid curve is for two sets of cavity with dipole-mode frequencies differing by 200 kHz; the dashed curve is for including cavity-parameter changes due to the rf feeds; the dash-dotted curve is for combining the two strategies used in the last two curves.

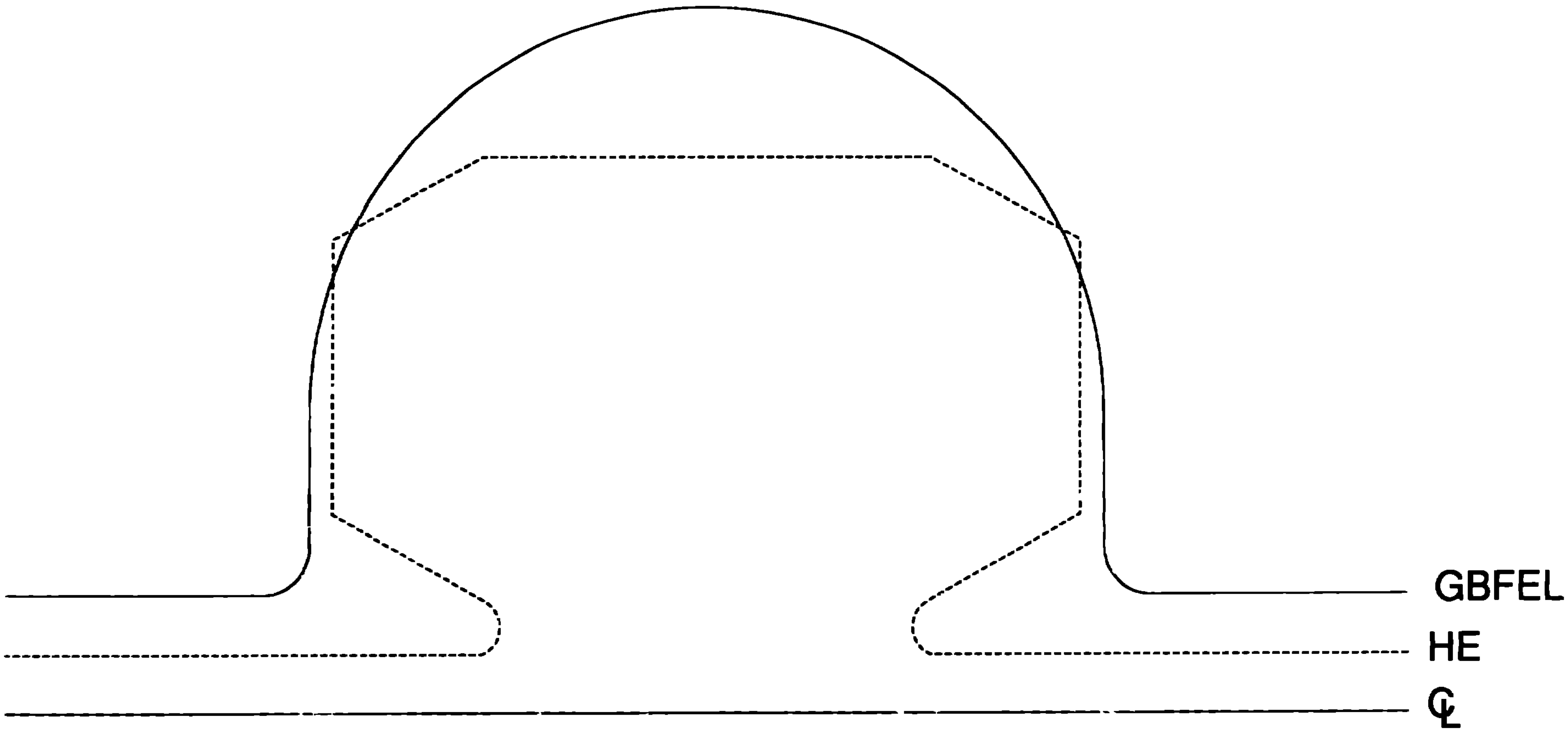


Figure 1

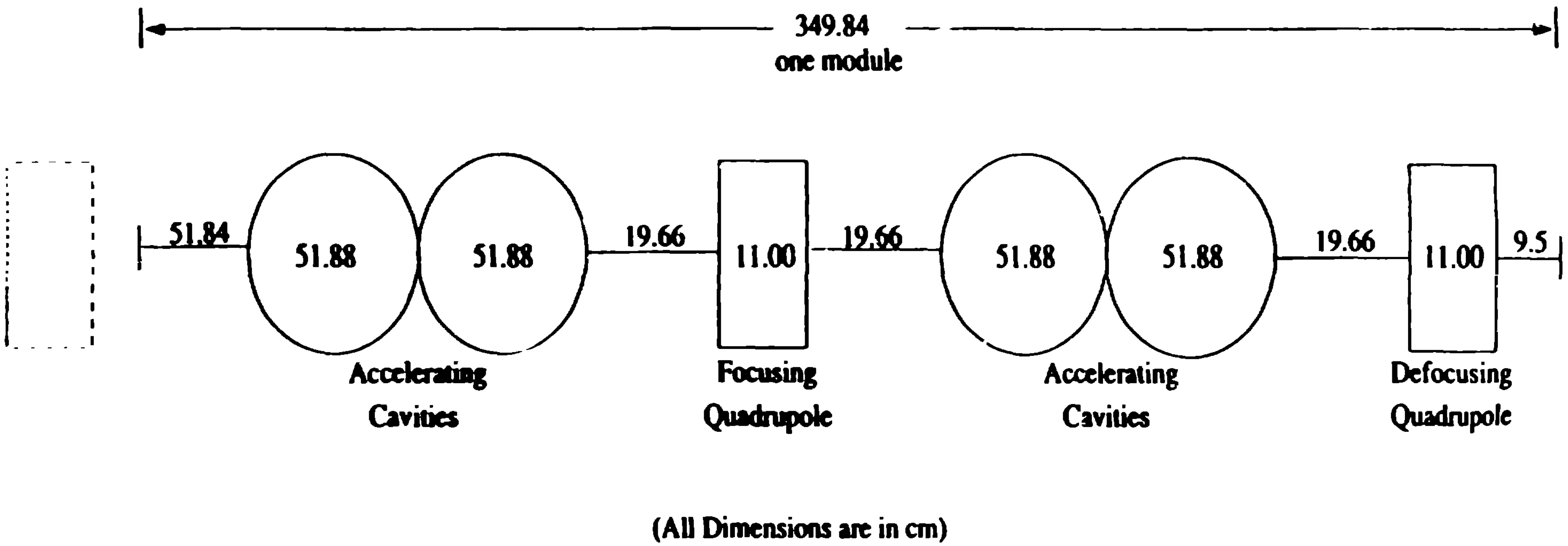

349.84
one module
51.84
51.88
51.88
19.66
11.00
19.66
51.88
51.88
19.66
11.00
9.5
Accelerating
Cavities
Focusing
Quadrupole
Accelerating
Cavities
Defocusing
Quadrupole
(All Dimensions are in cm)

Figure 2

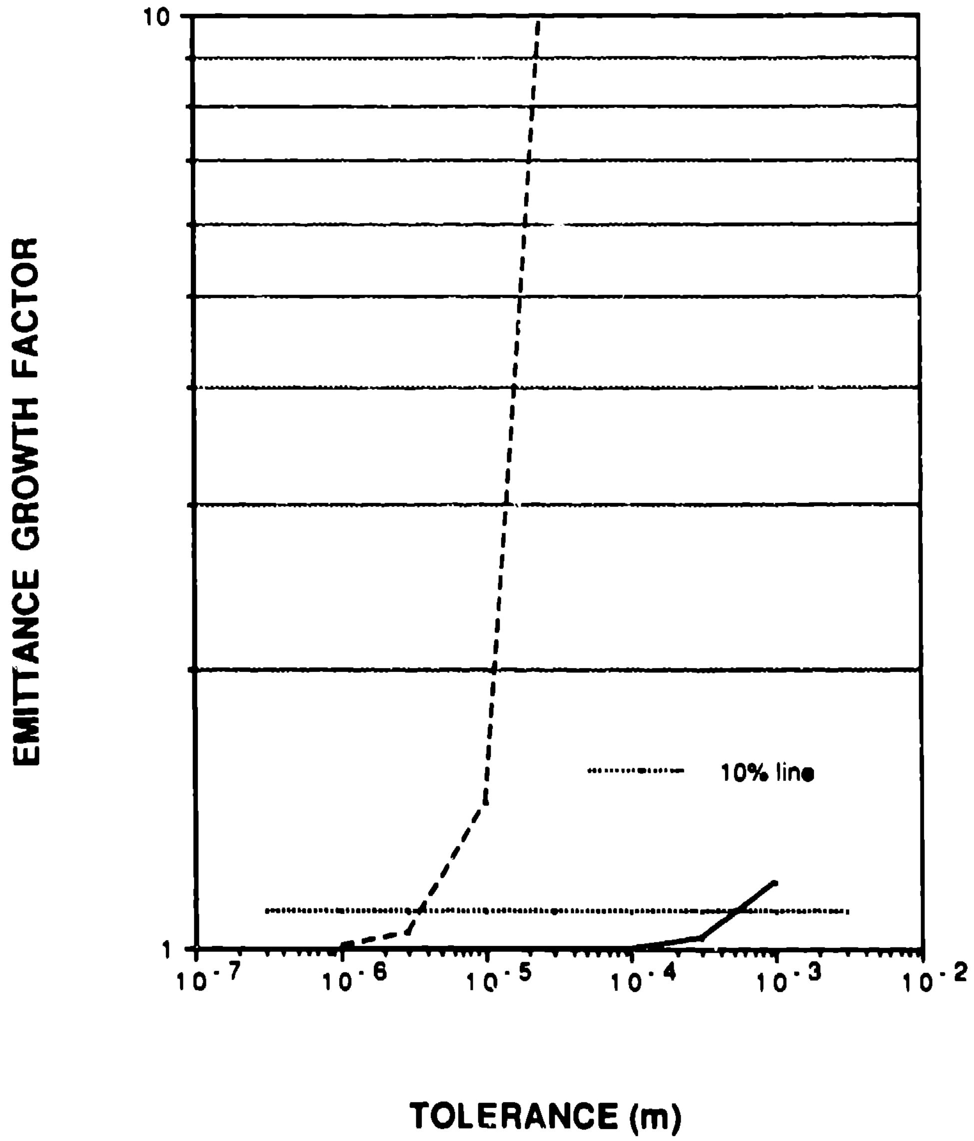
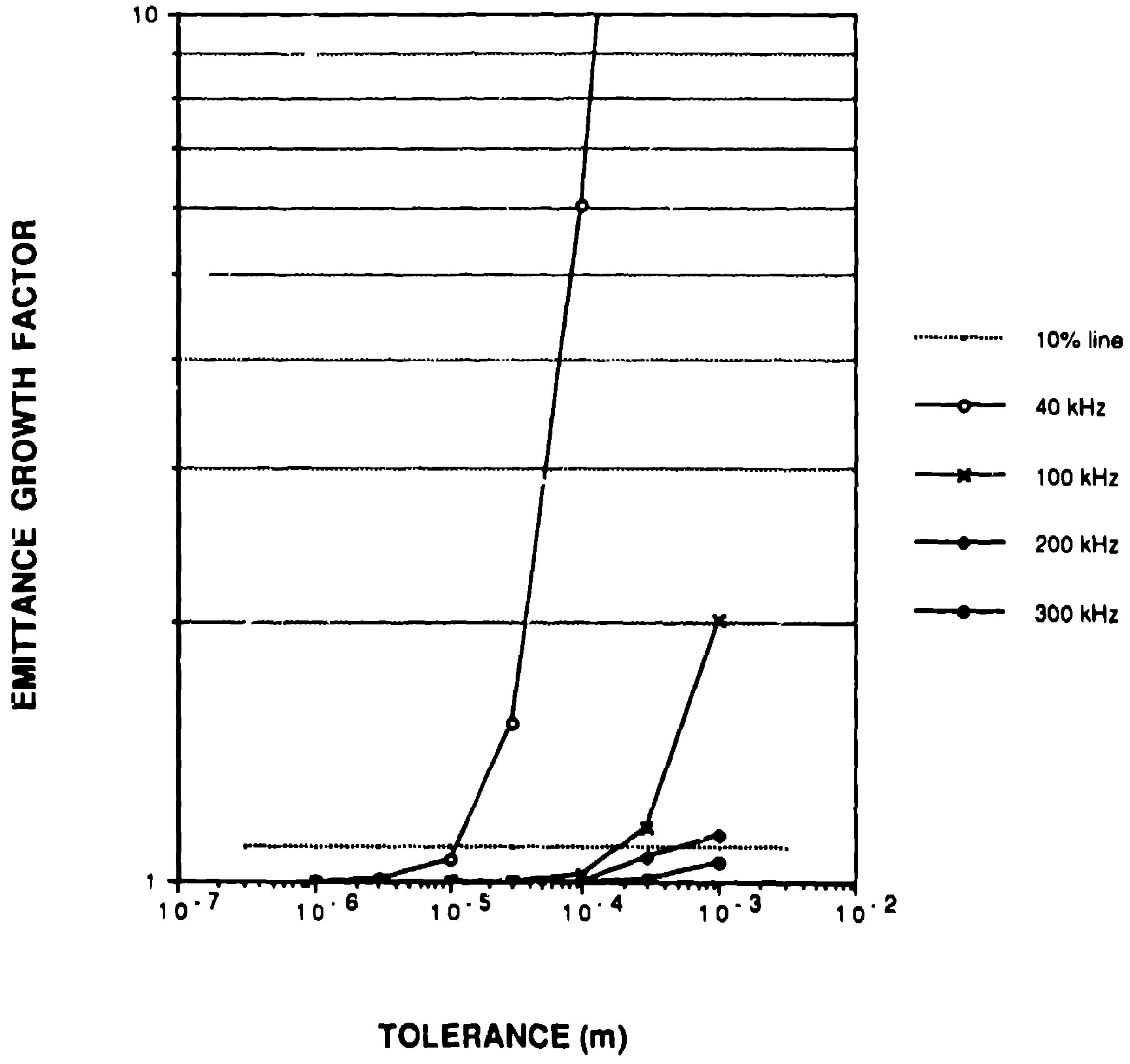
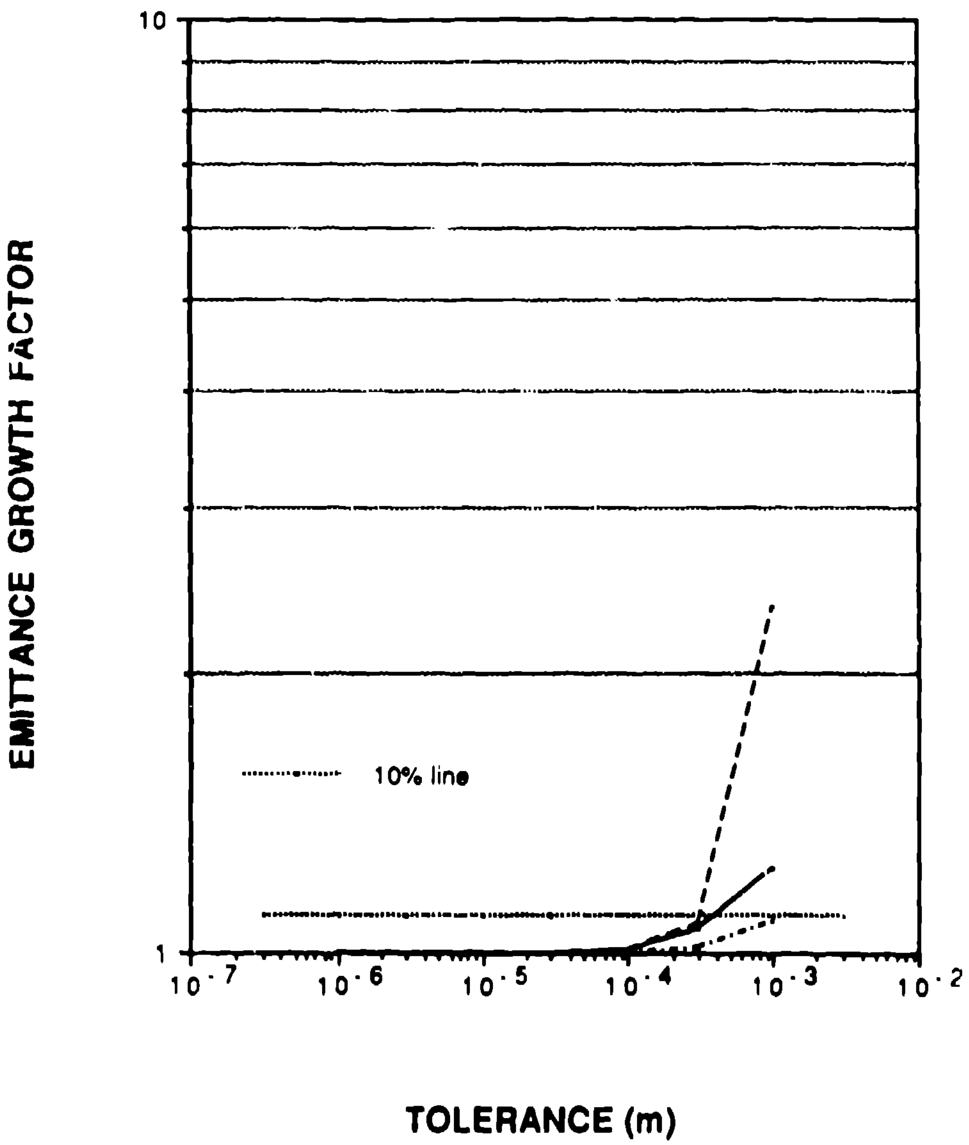

10
1
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
EMITTANCE GROWTH FACTOR
TOLERANCE (m)
10% line

Figure 3



10
1
EMITTANCE GROWTH FACTOR
10% line
40 kHz
100 kHz
200 kHz
300 kHz
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
TOLERANCE (m)

Figure 4



10
1
10% line
EMITTANCE GROWTH FACTOR
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
TOLERANCE (m)

Figure 5